Nitrate Response Functions for Watersheds

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Abstract
Groundwater flow models are often used to assess the impact of non-point source contaminants, and in particular nitrate, on river and well water quality. When using a particle tracing approach, the nitrate response function at a stream or well, \( C(T) \) \([M/L^3]\), can be generated by tracking nitrate inputs on a particle-by-particle basis. This methodology accounts for spatial and temporal variations in nitrate concentrations in groundwater recharge, as well as denitrification in the subsurface (Kauffman et al. 2001). Conversely, \( C(T) \) may be calculated using the convolution integral:

\[
C(t) = \int_0^\infty C_{in}(t - T) f(T) e^{-kT} dT
\]  

(1)

where \( f(T) \) \([1/T]\) is the transit time distribution for groundwater, \( C_{in}(t - T) \) \([M/L^3]\) is the spatially averaged nitrate input concentration, and \( k \) \([1/T]\) is the first order rate of denitrification in the subsurface (Malowzewski and Zuber 1982). The exponential lumped parameter model (ELPM) is one option that can be used to estimate \( f(T) \) as well as its integral, the cumulative frequency distribution (CFD) of transit times (Haitjema 1995a).

The advantage of the ELPM is that it is based off of spatially averaged hydrologic properties and hence easy to calculate; it also appears to be very robust, at least for large regional watersheds. We compared the performance of the ELPM with MODFLOW-MODPATH models developed for the Kirkwood-Cohansey Aquifer System (Kauffman et al. 2001) and Delmarva Watersheds (Sanford and Pope 2013). For large regional watersheds comprised of a single sand and gravel aquifer, the CFDs generated by the ELPM and MODPATH are similar (Figure 1). In all cases, the ELPM exhibits fewer transit times in the very short and very long ranges, primarily due to the presence of weak sinks. It is noted that, while the weak sink influence on the MODPATH CFD is small for these large regional watersheds, it is more pronounced for smaller sub-watersheds.
When land usage and associated nitrate inputs do not exhibit a distinct pattern, it appears that the spatially averaged nitrate input for the convolution integral is an appropriate assumption. For example, in the Maurice Watershed, land usage is scattered (see Figure 2a). In this case, both particle tracing, which explicitly accounts for the detailed nitrate input pattern, and the LPM, which uses a spatial average, simulate similar nitrate response functions (see Figure 2b).

We tested the impact of alternative land use patterns in the Maurice Watershed. For the case where land use boundaries coincide with (ground)watershed boundaries, the ELPM still simulates similar results to particle tracking. However, when land use boundaries approximate isochrones, the spatially averaged nitrate input performs poorly. For example, in Figure 3, high nitrate inputs are adjacent to the main branch of river; this area is associated with short transit times. Conversely, low nitrate inputs are
associated with the longer transit times near the watershed boundary. Subsequently, the nitrate concentrations in surface waters increase too slowly in the ELPM simulation when compared to MODPATH, see Figure 3.

The preceding simulations assume advective transport of nitrate in both the ELPM and particle tracking approaches. Luther and Haitjema (1998) show through numerical simulations that the impact of dispersion due to differential hydraulic conductivity layers with depth is minimal. In this study, we tested the impact of dispersion on the shape of the CFD using MODFLOW-MT3D simulations in a hypothetical watershed designed to simulate a typical sand and gravel aquifer. We found that even in unrealistically high cases of longitudinal and transverse dispersion, the CFD did not vary significantly from the non-dispersion case.

It appears that the two most important limiting factors for generating nitrate response functions with the ELPM are weak sinks and certain land use patterns. Both factors can be accounted for with analytic element models, which are free from the numerical artifacts related to cell-discretization in, for instance, MODFLOW (Abrams 2013). We successfully replicated the CFD and nitrate response function in the Maurice Watershed using GFLOW (Haitjema 1995b), both for the entire watershed and for smaller sub-watersheds influenced by weak sinks.

In the Maurice Watershed, dissolved oxygen levels are high enough that denitrification was assumed to be inhibited at all depths in the aquifer. In many watersheds, however, denitrification increases with depth as the dissolved oxygen concentration decreases. In an idealized watershed (semiconfined with constant recharge, saturated thickness, and porosity), groundwater age \( t \) [T] has the following relationship with aquifer depth \( z \) [L]:

\[
t = -\bar{\epsilon} \ln(1 - z/H)
\]  

(2)
where \( \tilde{t} \) [T] is mean groundwater age and \( H \) [L] is the saturated thickness. As a result, Equation (1) can be broken up to simulate different rates of denitrification over multiple time intervals as derived from Equation (2). We used this approach to simulate two hypothetical cases: A) denitrification occurring only in the lower 2/3 of the aquifer and B) no denitrification. Figure 4 shows the nitrate response function and (average) nitrate concentrations with depth for these hypothetical cases. The two nitrate response curves are similar for both cases in the first few years of nitrate applications (Figure 4a); the nitrate concentrations with depth are also similar (Figures 4b and 4c). Only when the older groundwater discharges to the stream do the CFDs for the two cases begin to diverge; similarly, the average concentrations with depth diverge at 10 m, which is where denitrification begins. We found that the ELPM and GFLOW models of the Maurice Watershed generated similar results to one another for multiple hypothetical cases of denitrification with depth.

Figure 4. a) Nitrate response functions for two hypothetical basins, Basin A (which underwent denitrification in the lower 60 ft of the aquifer) and Basin B (which underwent no denitrification). b) Average nitrate concentrations with depth in Basin A for 4 different years. c) Average nitrate concentrations with depth in Basin B for 4 different years.
References


Analytical models of groundwater-surface water interaction

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Abstract

Anderson (2005) investigated approaches for modeling concentrated vertical flows to surface water features in Dupuit models. Exact solutions for flow to a stream with no penetration and in direct connection with the aquifer were compared to Dupuit solutions which contain a fictitious leaky stream bed. The leaky stream bed incorporates the head losses due to vertical flow in the aquifer that are neglected in a standard Dupuit model. Three distinct flow regimes, dependent on regional flow conditions and stream geometry, were identified. Anderson showed that treating the stream bed resistance as an effective parameter results in values that are strongly dependent on the flow regime in the aquifer, especially for narrow streams. Anderson also showed how to remove all dependence on the flow field by defining two effective parameters in the Dupuit model.

Recently, that conceptual model has been criticized as being unrealistic, in that the river sits on top of the aquifer without penetration and without stream bed clogging (Miracapillo and Morel-Seytoux, 2014). Miracapillo and Morel-Seytoux (2014) claim that understanding the effects of partial penetration and flow asymmetry is critical in defining cell conductances for use in MODFLOW. In an attempt to deal with both, they present numerical models in the vertical plane and consider effects of mild asymmetry. Their results are based on the semi-analytical work of Morel-Seytoux et. al (2009, 2014), which considered zero penetration and a symmetric flow field. In application to asymmetric flow, they consider a narrow range of flow conditions that includes only one of the three possible flow regimes.

Here, we reconsider the results of Anderson (2005) and examine further the dependence of the effective bed resistance on flow conditions. We find that, while the effective value of the bed resistance is strongly dependent on the flow field, the error in head produced by an incorrect choice of parameter is small. We explain this feature of the flow field and present guidance for selection of stream bed resistance in Dupuit models. In addition, we present analytical models of flow to clogged stream beds (Figure 1), flow to partially-penetrating streams (Figure 2), and consider other issues not addressed in the original paper. These features are incorporated readily into the model of Anderson (2005) by conformal mapping with the choice of a convenient reference plane. By examining the more general flow cases, the importance of the original conceptual model of flow to a non-penetrating stream in direct connection with the aquifer becomes clear.

Key words: groundwater-surface water interaction, flow regime, river conductance

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Figure 1: Example flow fields for varying degrees of stream bed clogging $c^* k / H$, where $c^*$ is the average resistance of the stream bed: (a) $c^* k / H = 2.6$, $k^* / k = 0.1$, (b) $c^* k / H = 1.3$, $k^* / k = 0.2$, (c) $c^* k / H = 0.52$, $k^* / k = 0.5$, and (d) $c^* k / H = 0.26$, $k^* / k = 1.0$. In all cases $Q_r / Q_l = -0.5$, and the average thickness of the stream bed is $H^* / H = 0.26$. The thickness of the bed is exaggerated for clarity.
Figure 2: Example flow fields for varying degrees of penetration of the stream bed ($d/H$): (a) $d/H = 0$, (b) $d/H = 0.18$, (c) $d/H = 0.35$, and (d) $d/H = 0.57$. In all cases $Q_r/Q_t = -0.5$. 
References


Stream depletion and TTIm

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Abstract

Wisconsin is a riparian state and property owners are guaranteed reasonable use of groundwater. However, due to over-allocation in agricultural regions of the State, permitting new high-capacity wells has become a contentious issue. The State Administrative Code is at least 10 years behind other riparian states, such as Michigan, in defining reasonable use in relation to protecting the State’s water resources. With no legislative guidance, the State Department of Natural Resources is now being directed by lawsuits, budget bills, and court rulings which have alternately restricted and then expanded the scope of their review responsibilities beyond their abilities. The DNR has stopped approving high-capacity well permits while the state attempts to develop a new review process. The DNR is focusing their attention on the ecological impacts to surface waters due to groundwater withdrawals (Kendy et al, 2012), and has, in part, adopted Michigan’s rules as guidance. Michigan law defines an Index Flow for all surface water basins in the state, and further defines allowable cumulative stream depletion as a percent of the Index Flow.

We present a case study, including field work and stream depletion modeling, conducted for the purpose of permitting high capacity wells for a proposed sand mining site in western Wisconsin. We discuss how the project was designed to address the possible concerns of the DNR, in the absence of a well-defined review process. The study focuses on field testing and stream flow monitoring, and minimizes groundwater flow modeling. Deep exploratory borings, two 72 hour pumping tests, and borehole geophysical studies were conducted to develop a hydrogeological conceptual model. During a period of base flow conditions, flow measurements were made at 34 stream crossings in the watershed and correlated to USGS gage data to estimate Index Flows. Finally, stream depletion modeling was performed with TTIm (Bakker, 2012). Results were reported as a percent depletion of the Index Flow for all streams in the watershed.

TTIm proved to be an ideal tool for this type of analysis. It nicely fills the gap between analytical tools currently used by regulators for stream depletion modeling (Reeves, 2009) and more complex numerical models. In particular, TTIm allows for realistic stream geometry and the ability to assess all streams within a watershed. A TTIm model requires minimum data, but is flexible enough to simulate general aquifer features. Unlike many numerical models, a TTIm model is easily reviewed, and reproduced. The Wisconsin DNR is currently assessing TTIm for use as a regulatory screening tool.

Key words: groundwater-surface water interaction, analytical modeling, stream depletion

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References


Application of the Exact Solution for a Stratified Coastal Aquifer

An exact solution to the case of a stratified coastal aquifer using a vertically integrated discharge potential was developed by Dr. O.D.L. Strack and published (under review) in Water Resources Research [?]. The solution applies to steady-state coastal interface flow where the aquifer is divided into horizontal layers of varying hydraulic conductivity overlying an impermeable base. The Ghyben-Herzberg relations are utilized, and the saltwater and freshwater are each held at a constant density. The fresh-groundwater flows to a vertical outflow face which separates it from the static salt-groundwater. The solution satisfies the partial differential equation applied in the absence of an interface for any combination of steady-state potential functions that are functions of location and strength only (i.e., these features do not alter the relationship between head and potential).

The compatibility aspect of this new formulation is the focus of this presentation. It will be shown that this stratified coastal interface solution can be integrated with other pre-existing codes such as MLAEM to solve current saltwater intrusion problems. The solution is thus applied to the Biscayne Aquifer in southern Florida; an unconfined limestone aquifer which produces the primary source of fresh drinking water for Miami and the Florida Keys, and possesses a high risk for saltwater intrusion. MLAEM is used to solve for the discharge potentials in the Biscayne aquifer, with the inclusion of features such as constant head boundaries to represent the coast, lakes, rivers, & canals, as well as zones of infiltration and wells. The model is calibrated using detailed data from two USGS water resources investigations reports (WRI 78-107) and (WRI 90-4108) [?][?].
From the MLAEM computed discharge potentials we then solve for the head and interface elevation using the exact solution for a stratified aquifer, which has been implemented in MATLAB.

References


Interactive multi-layer analytic element modeling with Jupyter Notebooks

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Jupyter Notebooks (formerly IPython Notebooks) are powerful interactive environments to run Python code (other languages are also supported, see https://jupyter.org). As stated in Bakker (2014): “A [Jupyter] Notebook combines Python scripts with text, mathematics, and graphical output into a single document. The amazing part is that a Notebook can actually be executed, which means that all Python code in the Notebook is run and all output is regenerated. A Notebook is a full executable report of the entire modeling endeavor. Notebooks can be sent directly to clients, or can be converted to static pdf or html files. Entire books are written as [Jupyter] Notebooks. It is not inconceivable that scientific journals will accept (or require?) modeling papers as [Jupyter] Notebooks in the future.” In this presentation, a simple analytic element model is built from scratch using object oriented programming in Python in a Jupyter Notebook. More advanced examples are shown using the Python Analytic Element codes TimML and TTim (e.g., Bakker, 2013).

References
The Analytic Element Method as a Probability Engine

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ABSTRACT

Context

The Analytic Element Method epitomizes deterministic groundwater modeling. The Analytic Element Method allows/requires an explicit specification of geometric details of the model, with a one-to-one correspondence between each element and the element’s mathematical representation. The Analytic Element Method constructs models that satisfy the partial differential equation everywhere, satisfy continuity of flow everywhere, and satisfy the boundary conditions at an unprecedented precision.

As a numerical laboratory [e.g., Barnes and Janković, 1999] the Analytic Element Method offers concise, precise, repeatable results, limited only by machine precision. The innate ability of the Analytic Element Method to model at the small scale, the large scale, and simultaneously across scales offers insights that are otherwise hidden from our sight. See, for example, Steward and Janković [2001], Janković and Fiori [2010], and Fiori and Janković [2005].

Perspective

As an engineering modeling tool, the Analytic Element Method is capable is generating very, very precise wrong answers. As with a calculator that shows sixteen digits, the user may be seduced into confusing precision with accuracy. The accuracy of an engineering model depends not only on the conceptual model and the modeling tools, but also on the input data – the measurements from the field.

We advocate that measurements⁠¹ be understood as stochastic quantities, fundamentally uncertain, and we adopt a Bayesian framework (e.g., Vick [2002] or Jeffrey [2004]). This differs from previous attempts to integrate the Analytic Element Method and stochastic modeling by eliminating the prior, or asymptotic posterior, assumptions of normality [e.g Brown and Barnes, 1994].

⁠¹By measurements, we include head measurements, flow measurements, estimates of recharge, a few transmissivity estimates from pumping tests, a multitude of noisy transmissivity estimates from specific capacity tests, etc.

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The Bayesian formalism

Bayes’ Theorem\(^2\) gives us

\[
  f(P|M) = \frac{f(M|P) \cdot f(P)}{\int f(M|P) \cdot f(P) \, dP} \quad (1)
\]

where\(^3\)

- \(f(P|M)\) denotes the joint conditional density function of the model parameters, \(\text{matcalP}\), given measurements \(M\);
- \(f(M|P)\) denotes the conditional density function of the measurement \(M\) given the model parameters \(P\); and,
- \(f(P)\) denotes the joint prior density function of model parameters \(P\).

Kullback-Leibler

A datum, or a small subset of data, may be influential if it is inconsistent with the surrounding data, conflicts with the conceptual model, or is geographically isolated and the computations give it exceptional weight.

We characterize the influence of a data subset by the impact the subset has on the posterior distributions of the key parameters. We compare the posterior distribution, say \(F\), computed using all of the data, with the posterior distribution, say \(G\), computed using all of the data excluding the subset. We quantify the change in the posterior distributions using the Kullback-Leibler divergence.

The Kullback-Leibler divergence is an asymmetric, quantitative measure of the difference between two probability distributions [Kullback and Leibler, 1951, Eguchi and Copas, 2006, Wikipedia, 2013b]. For alternative distributions \(F\) and \(G\) of the random parameter \(\alpha\), with associated density functions \(f(\alpha)\) and \(g(\alpha)\), the Kullback-Leibler divergence is defined by the integral

\[
  D_{\text{KL}}(G||F) = \int_0^{2\pi} \log_2 \left( \frac{g(\alpha)}{f(\alpha)} \right) g(\alpha) d\alpha \quad (2)
\]

The Kullback-Leibler divergence quantifies the information lost when \(F\) is used to approximate \(G\); the associated units are [bits]. The Kullback-Leibler divergence is easily computed using numerical integration.

Poeter and Anderson [2005] used the Kullback-Leibler divergence to rank-order competing groundwater models based on parsimony and data fidelity. We use the Kullback-Leibler

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\(^2\)The elementary form of Bayes’ Theorem is a direct application of the definition of conditional probability:

\[
  Pr(A|B) = \frac{Pr(B|A) \cdot Pr(A)}{Pr(B)}
\]

Equation (1) is an extension of this elementary form to conditional density functions. See, for example, Wikipedia [2013a].

\(^3\)As a notational standard, we use “\(f\)” to represent density functions. In any specific case, the particular density function is identified by the arguments. Thus, \(f(N)\) is a different density function than \(f(k)\). This operator overloading approach is a departure from the use of superscripts and subscripts, over-scripts and under-scripts, to distinguish different functions, which may be more familiar to many readers. Nonetheless, the chosen notation is compact and unambiguous.
divergence to rank-order the data based on influence, as proposed by Hartigan [1968] and generalized by Millar and Stewart [2007].

We loop through the data set leaving out each observation, one at a time, and compute the associated Kullback-Leibler divergence. The more influential data have the higher values of the Kullback-Leibler divergence. This process can also be carried out for pairs and triples of the data, thereby identifying the more influential small subsets.

Unlike a simple sum of squares, the Kullback-Leibler divergence can be computed for individual model parameters, allowing us to identify which measurements are more influential for each parameter. Some parameters are more sensitive to one set of measurements and other parameters are more sensitive to a different set of parameters. The Kullback-Leibler divergence allows us to quantify these differences in an objective, repeatable fashion.

**Computational efficiency**

While the recommended methods can be applied to most computational groundwater tools, the Analytic Element Method offers unique computational shortcuts and efficiencies.

**Deliverables**

Three examples demonstrating what, how, and why the Bayesian formalism could be embraced by the Analytic Element Method community are presented.


Transient Groundwater Flow Simulation Using Laplace Transform Series Solution Methods

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A semi-analytical modelling approach for simulating two- and three-dimensional transient groundwater flow in a piecewise heterogeneous aquifer with time-varying surface water forcings is presented. The solution is obtained by solving the modified Helmholtz equation in Laplace transform space using a series solution method. Boundary and continuity conditions are met with a high degree of precision along irregularly shaped surfaces in both cross-sectional and plan view aquifer models. Irregular geometry can be handled without the need for complex coordinate transforms or special treatment of different aquifer interface shapes. Various test cases are presented and the accuracy and appropriateness of the method is discussed.
Series Solution Methods for Irregular Domains: A Primer

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Series solution methods (SSMs) are a close cousin of the analytic element method (AEM). Both are Trefftz methods, i.e., mathematical methods which generate solutions to linear partial differential equations via superposition of basis functions which themselves meet the governing equation exactly. The primary distinction between the two is that AEM basis functions tend to be defined for infinite domains, whereas the series solution method is generally restricted to finite domains. Both approaches can be applied to satisfy boundary conditions with a high degree of accuracy. Both can be applied to any number of problems in groundwater flow, heat transfer, mechanics, and acoustics. However, implementation of the series solution method is in some ways a bit more straightforward.

The SSM approach relies upon basis functions generated using the classical method of separation of variables, which has been historically reserved for regular domains where the domain boundaries are defined along surfaces of constant coordinate. However, the monotonicity of these basis functions in their “warp” direction (e.g., \( y \)-direction) and orthogonality in the “weft” direction (e.g., the \( x \)-direction) enables the set to form a complete basis along any single-valued curve (e.g., \( y'(x) \)) via projection. Because the basis is complete, it can be used to match arbitrary boundary conditions without complex orthonormalization procedures, effectively strengthening the method of separation of variables. This concept will be expounded upon for the first time here.

The SSM approach is particularly useful for simulating problems with irregular and complex geometry, and has been applied to simulate groundwater flow in a number of relatively complex domains in 2D and 3D; it has shown particular promise in application to free boundary problems. Here, I will provide an overview of series solution methods, discuss the history of their development, and highlight commonalities with AEM and means of integrating series solutions and AEM.
Application of AEM for creation of a large, continuous plate-shaped injection below a canal

Willem J. de Lange, Deltares

Abstract

Seepage of groundwater to canals – e.g. occurring after a significant lowering of the surface water level - may cause serious problems for both the stability of the canal bottom and for agriculture, house settlement, foundation constructions in the vicinity of the canal. This occurs in a city area in the southern part of the Netherlands.

Mitigation may come from a construction that generates significant resistance to the seeping groundwater and causes sufficient stability of the canal bottom. However, this requires construction under water and below the present canal bottom and over an area (40 x 1000m) that exceeds any existing experience of continuous injection.

An AEM model is used to develop a way of injection that generates a plate shape resistance over the large area (40,000m2) at several meters in a sand aquifer below a canal under reconstruction.

Parallel to this hydrological research a chemical research is undertaken to combine bulk chemical substances to a resistance layer that is also found in nature in aquifers similar to the existing case.

This research is in progress.
Analysis of a porous layer surrounding a large tube for large domain infiltration in deltaic aquifers

W.J. de Lange, Deltares

Abstract.

Large cities in deltas all over the world encounter negative consequences of unlimited groundwater abstraction. These cities being in strong development, large amounts of pipes are expected to be constructed coming years e.g. for sanitation, subways, drinking water supply, etc.

The present research is based on AEM models and analytic expressions and aims to analyze the impact covering pipes with a porous layer in order to increase the contact surface with the generally strongly layered and low permeable aquifers in deltas. The aim in practice is to infiltrate water through these large contact surfaces to prevent the city for negative consequences, such as settlement.

The AEM models describe the groundwater flow in a vertical section in the near vicinity of a large circular pipe (metro tube) with a porous bounding layer in different combinations of sub-aquifers and sub-aquitards in a deltaic low permeable aquifer system. The analytic expressions are used to compare the feasibility and effectiveness of different means of injection in such aquifers, such as horizontal large metro tubes and small infiltration pipes versus vertical wells and large constructions such as metro railway stations. The research is still in progress.
Application of AEM and Artificial Neural Network for Optimization of Groundwater Extraction

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Abstract: In this study, coupled Artificial Neural Network (ANN) and Particle Swarm Optimization (PSO) model is developed for the management of groundwater in Dore river basin, France. Analytic Element Method (AEM) based flow model has been used to generate the dataset for the training of ANN model.

Ground management problems are typically solved by simulation-optimization model. In this approach, complex numerical model are used to simulate groundwater flow and/or contamination transport. These numerical models take a lot of time and become computationally expensive.

The developed model has been applied to minimize the pumping cost of the wells. The location of pumping wells has also been taken as decision variables and ANN model has been applied to find out the optimal location of wells. Optimal number of wells is calculated by developing the ANN-PSO model for different number of wells and comparing their total cost correspondingly.

Results show that well-trained ANN-PSO model with AEM is capable to identify the optimal location of wells. Results of ANN-PSO model are found close to the results obtained from AEM-PSO model by reducing the computational burden considerably.

Key Words: Groundwater Modeling, Groundwater management, Analytic Element Method, Artificial Neural Network, Particle Swarm Optimization.

On Transit Time Distributions in Watersheds

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Abstract

The transit time distribution (TTD) of groundwater in a watershed plays a critical role in defining long term impacts of non-point source pollution on surface waters and wells (Maloszewski and Zuber 1982; McGuire and McDonnell 2005; McDonnell et al. 2010). These TTD’s may be obtained in various ways, most often by use of a groundwater flow model in combination with a particle tracking procedure, e.g. GFLOW or MODFLOW with MODPATH. Alternatively, a lumped parameter model (LPM) may be used, often with one or two parameters to be determined through calibration to measured transit times in the field. While calibrated lumped parameter models are much quicker (thus cheaper) to develop than a particle tracking model, they do require field measurements of transit times, which are rarely available in practice.

Haitjema (1995) demonstrated that under some simplifying assumptions the TDD and thus also the cumulative frequency distribution (CFD) of transit times can be approximated by a simple exponential function. Defining $F(T)$ as the groundwater discharge $Q(T)$ with transit times of $T$ or smaller divided by the total groundwater discharge $Q$ from the watershed, the CFD is found to be:

$$F(T) = 1 - e^{-\left(\frac{T}{\bar{T}}\right)}$$  \hspace{1cm} (1)

where

$$\bar{T} = \frac{nH}{N}$$  \hspace{1cm} (2)

with porosity $n$, average saturated aquifer thickness $H$, and average areal recharge rate $N$. Equation (1) thus represents an LPM whereby no calibration
to measured transit times is necessary. Instead, measured or estimated average values for $n$, $H$, and $N$ suffice. For (1) to be exact, the average transit time $T$ must be constant over the watershed. Luther and Haitjema (1998) investigated the robustness of (1) by varying $T$ over a hypothetical watershed and numerically determining the CFD by releasing thousands of particles uniformly over the watershed and tracing them to the stream network. They found that as long as variations in the parameters in (2) are sufficiently random, (1) is a good approximation of the actual (modeled) CFD.

Abrams et al. (2013) found that these previous studies did not consider the impact of weak sinks, which are surface waters or wells that do not extract water from the entire aquifer thickness. Weak sink streams, for instance, only receive water from the upper aquifer zones and thus allow water to pass underneath to some other discharge point (a well or other surface water). The impact of a weak sink on the CFD can be profound as shown in Figure 1, although this impact appears to be less prominent in larger watersheds with both weak and strong sinks. We will investigate the impact of weak sinks on the practical use of the LPM as well as investigate the effects of sloping aquifer bottoms and three-dimensional flow in cases where the Dupuit-Forchheimer approximation is inappropriate.

Figure 1. The effect of a weak sink on the CFD. Path lines are sketched in a cross section of a watershed containing a weak sink and a strong sink stream. The colors in the CFD diagram correspond to the (sub)watersheds colors in the cross-section. The dashed blue line is the CFD from the LPM represented by equation (1). The light-brown line that weaves around the blue and yellow line is the CFD for the entire watershed.
Finally, we will show how the use of MODFLOW-MODPATH for the construction of CFD's can be improved upon. Abrams (2013) presented a simple correction on simulated transit times in models with large cell sizes, hence models in which the width of streams is often much exaggerated. This has been accomplished by replacing the porosity $n$ in MODPATH by $n^*$ defined as

$$n^* = \frac{n}{1+a}$$

(3)

where $a [-]$ is defined as $a=w/L$ with $w$ being half the average (stream) cell width in the MODFLOW and MODPATH model and $L$ being the average distance between the stream cell boundary and the nearest water divide. This correction has been derived from an analysis in Luther and Haitjema (1998) regarding the impact of wide streams on the CFD. Because $w$ and particularly $L$ vary in a real watershed the correction is approximate, but rather effective as demonstrated in Figure 2.

Figure 2. High-, intermediate-, and low-resolution models result in different CFD’s, see “Original” curves. Once adjusted for the effect of cell size on the stream width the CFD’s are nearly the same, as they should be, see “Adjusted” curves. After Abrams (2013).
The need for this correction can be judged in advance by comparing the values of $n$ and $n^*$. This analysis also illustrates the value of using analytic element models for generating CFD's, as these do not suffer from cell size problems.

**References**


Some interesting analytical calculations on the concept of vertically integrated flow

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Vertically integrated flow is an appropriate approach to analytically assess the small-scale sustainability in groundwater engineering realm. In this regard, we show several cases to compare the available analytic solutions with the models based on the concept of vertically integrated flow. The objective of this presentation is to focus on the analytical and mathematical aspects of the concept and to show how discharge potentials and heads are derived using proper power series as well as related mathematical manipulations on them.

In addition, the boundary conditions and the geometry of different cases are also illustrated and discussed. At the end, related plots showing the discharges, heads and the comparison between the cases are depicted as well. It is worthy to mention that understanding the mathematics behind conceptual models is very helpful to correctly create and run the models although software developers tend to create such user-friendly models that the users are allured to ignore the complexity behind the software but that’s not the case.
A hybrid iterative/direct method for new high-order head-specified line-elements

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We present equations for high-order analytic elements for modeling line-doublets, line-dipoles and line-sinks. We apply a new hybrid direct/iterative method of solution for head specified analytic elements which is an improvement over the similar approach presented by Bandilla et al. [2007]. The approach is implemented in Matlab®; comparisons of computational times as compared to alternative approaches are presented.

References

Application of new high-order analytic elements to modeling inhomogeneities

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We apply new very high order analytic elements to the modeling of inhomogeneities in the hydraulic conductivity, and use these to study the behavior near singularities such as corner points and intersections. We apply the technique to investigate the flow pattern near the intersections of cracks filled with highly permeable material in a uniformly permeable medium.
A formulation for vertically integrated groundwater flow in a stratified coastal aquifer

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We present the comprehensive discharge potential for steady three-dimensional flow in horizontally stratified coastal aquifers with a horizontal base and a vertical coastline. The gradient of this comprehensive potential gives the vertically integrated discharge throughout the aquifer. The boundary values of the comprehensive potential along the coast can be computed precisely, given the geometry of the aquifer: the hydraulic conductivities of the strata, the elevations of the horizontal planes that separate the strata, and the elevation of the impermeable base of the aquifer relative to sea level. Boundary conditions of the comprehensive potential may either be given in terms of its gradient, or computed from given heads along the boundaries. The governing equation of the comprehensive potential is the Poisson equation in areas of infiltration and the Laplace equation elsewhere. The computation of interface elevations, piezometric heads, and the vertical distribution of flow, requires that an assumption be made regarding the relation between the comprehensive potential and piezometric heads. We adopt the Dupuit-Forchheimer approximation for this purpose and make use of the Ghyben-Herzberg equation. We present several applications of the approach, and find that the stratification may have a significant effect on the boundary value of the comprehensive potential, and thus on the flow rates in the aquifer.
Assessing groundwater sustainability using vertically integrated models

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We outline a methodology for assessing groundwater sustainability as applied to agricultural irrigation, based on vertically integrated flow modeling. We outline how to determine the distribution of vertically integrated flow across the boundaries can be assessed for farms using irrigation and wells. We explain how the effects of rivers and other features not penetrating the system fully can be modeled in an approximate manner and present equations for implementation in a single-layer model.
During the week of November 24 – 30, 2013, heavy rainfall occurred over several agricultural land tracts located in southern Miami-Dade County, Florida, east of the Everglades National Park (ENP). This resulted in some flooding of these areas. Initially, the flooding was partially attributed to the blockage of the remnant C-110 canal located to the south. A simple analytic element model of a portion of southern Miami-Dade County was constructed using the software GFLOW in order to evaluate the potential effects of plugs installed in the C-110 canal on ground water levels within the agricultural areas. Additionally, in order to evaluate the amount of easterly seepage from the ENP during the same time frame, a secondary modeling objective was to evaluate the percentage of seepage from the ENP that was captured by the C-111 borrow canal along the eastern boundary of ENP.

Computed steady state water levels based on average hydrologic conditions during the week of heavy rainfall were within the measured range of most of the ground water monitoring stations used for history matching. Additionally, computed net inflow rates for selected canal reaches were compared to ranges of measured inflow rates for the same period of record. The computed net inflow rate for each of these canal reaches was within its measured range.

The model was used to assess the effects of the C-110 canal plugs on ground water by running the model under the same conditions used for history matching, both with and without horizontal flow barriers installed at plug locations. The results indicate that the plugs have a negligible effect on ground water levels and flows within the agricultural land tracts located to the north of C-110. Furthermore, the calibrated model was also used to evaluate the percentage of ENP seepage across its eastern boundary that was captured by the C-111 borrow canal. Under the conditions modeled, it was found that most, if not all, of the ground water flow exiting ENP is captured by C-111.